

Long-term drift laser frequency stabilization using purely optical reference.

A. Rossi and V. Biancalana

*INFM UdR Siena - Department of Physics, University of Siena,
Via Banchi di Sotto 55, 53100 Siena, Italy.*

B. Mai and L. Tomassetti

*INFN Sez. Ferrara - Department of Physics,
University of Ferrara, Via Paradiso 12, Ferrara, Italy.*

(Dated: July 2002)

Abstract

We describe an apparatus for the stabilization of laser frequencies that prevents long term frequency drifts. A Fabry-Perot interferometer is thermostated by referencing it to a stabilized He-Ne laser (master), and its length is scanned over more than one free spectral range allowing the analysis of one or more lines generated by other (slave) lasers. A digital acquisition system makes the detection of the position of all the laser peaks possible, thus producing both feedback of both the thermostat and the error signal used for stabilizing the slave lasers. This technique also allows for easy, referenced scanning of the slave laser frequencies over range of several hundred MHz, with a precision of the order of a few MHz. This kind of stabilization system is particularly useful when no atomic or molecular reference lines are available, as in the case of rare or short lived radioactive species.

PACS numbers: 32.80.Pj, 42.50.Vk, 32.60.+i.

Keywords: laser frequency stabilization

RSI VOLUME 73, NUMBER 7 JULY 2002, pages 2544-2548

I. INTRODUCTION

Many techniques have been developed to stabilize both the long term and short term drift of laser frequencies. They mainly use reference frequencies obtained by cavity resonances or atomic or molecular transitions [1]. Many commercial lasers have built-in stabilization systems and analog or digital inputs that can be used with custom, external referencing systems. We developed a stabilization system to be used in experiments where no atomic line references are available. In particular, it has been designed to stabilize single-mode ring dye lasers and Ti:sapphire lasers. The system provides a voltage which can also be used as a feedback for other kinds of externally controllable lasers, and in particular for diode lasers.

This problem has already been faced and successfully solved in the framework of laser-cooling experiments involving short-lived radioactive species [2, 3], for which no atomic vapor can be used. Similar applications may arise when rare isotopes have to be excited. The peculiarities of our stabilization technique also allow for easy scanning of the stabilized frequency over broad ranges.

The technique makes use of an optical cavity whose length is scanned over more than a free spectral range (FSR) by means of a piezo actuator. The master laser and slave laser(s) beams are collimated and simultaneously analyzed, so that a multiple peak spectrum is observed. Finally, a reference signal is produced by reading the relative positions of the observed peaks.

Our implementation simplifies the one described in [2] by using a thermal control of the optical cavity length, instead of compensating the thermal drift with piezo actuators, thus making the use of high-voltage offset on the piezo unnecessary. This choice is similar to the one reported in [3] and it makes the piezo response more constant in time. Actually, the response of piezo actuators is non-linear, and the large values of DC offset needed to compensate thermal drift of the cavity length may dramatically change the slope of the response and hence the effect of the AC scanning signal. For this reason, differing from [2], we do not need a continuous re-calibration of the scan following the variation of the piezo response.

The same result could be achieved by using two separate actuators for thermal com-

compensation and for scanning, nevertheless our solution is easier and also allows for simpler construction of the cavity, because no fused quartz, invar or other materials with low thermal coefficient are needed. In fact, the compensation of the slow thermal drift of the cavity length does not need the fast response of a piezo actuator to be accomplished, moreover the thermal control does not suffer of the small range compensation which is intrinsic in the piezo. In our case the optical cavity was home-made in aluminium, and this choice also makes the cavity alignment fast and cheap, with the use of a simple device produced by a common tool machine.

The system is fully controlled by a computer program which operates a commercial ADC-DAC card. The program was developed in order to achieve relatively fast operation, continuous control of the cavity response, flexible adjustment of the feedback parameters, and on-time visual monitoring of the laser spectra.

Analysis of the error signal has also been implemented in order to characterize the performance of the system. All the digital controls were developed in LabView, making use of either a 16 bit or a 12 bit National Instruments card. No external electronics are needed apart from a very simple voltage-to-current converter used to supply the cavity heater. We used the program to stabilize only one laser with respect to the He-Ne, but other laser lines can be added and referenced with straightforward extensions of the program. In particular with this system we plan to stabilize a Ti:Sa ring laser working at 718 nm and a diode laser working at 817 nm, which will be used as cooling and repumping lasers in an experiment of magneto optical trapping (MOT) of Francium [4].

II. EXPERIMENTAL APPARATUS

The experimental apparatus is sketched in Fig. 1; it consists of a Fabry-Perot (FP) confocal optical cavity [1, 5], on which all the lasers are analyzed. An electric heater H (maximum power 10 W) fed back by the computer keeps the cavity at a temperature about 15° C above the room temperature, stabilizing the cavity length to the He-Ne line. The cavity length is then dithered over a range just wider than one FSR by means of a piezo actuator (P) which is directly driven by a 24 V waveform generator. The transmitted light is detected by a single amplified photodiode whose signal is directly acquired by PC. The computer feeds back both the heater through a voltage controlled current generator which

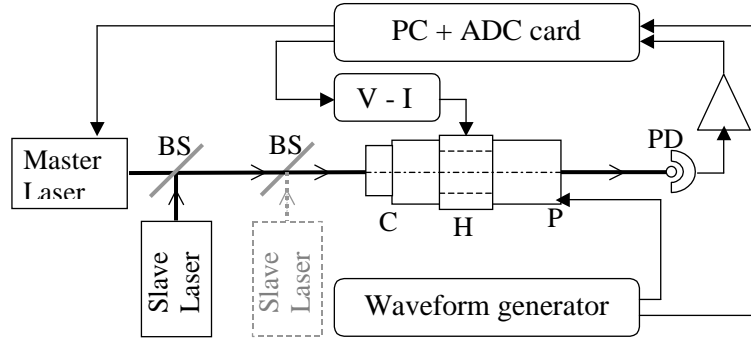


FIG. 1: Schematic of the Apparatus. The beams of the master and slave lasers are made collinear, at the beam splitter BS. Similarly the beams of other slave lasers can be added. V-I is a voltage-to-current converter. The length of the cavity C is slowly adjusted by controlling the mount temperature through the heater H, and is dithered with a piezo P over a range of the order of half a wavelength.

thermally stabilizes the cavity length, and the slave laser(s) with a suitable error signal.

A. The Fabry-Perot cavity

We built up several confocal Fabry Perot cavities having a 1.5 GHz free spectral range. The mirrors have a high reflectivity for the 633 nm He-Ne line and for other wavelengths which are 780 nm (diode laser for Rb lines), 590 nm (dye laser for Na lines), 718 nm (Ti:sapphire for Fr lines). Each set of mirrors has high reflectivity for two or more wavelengths. In this paper we report results obtained with the 590 nm device, by which we stabilized a (Coherent) ring dye laser used for experiments on sodium MOT's. The mirrors (1 inch, 5cm curvature radius) were provided by CVI (TLM1 series). The measured finesse is 70 for both the 633 nm and the 590 nm, consistent with the declared reflectivity ($> 99\%$). The mirrors are mounted on an Al tube adjustable in length, as represented in Fig. 2.

Such a mount is home-made by a standard tool machine, allowing for easy and effective centering of the optics at a very low cost. A thread is included in order to adjust the position of one mirror and to get an easy, precise match of the cavity length to operate in confocal regime. The non-adjustable mirror is mounted on a rubber o-ring and it is asymmetrically actuated by a low-voltage driven piezo (AE0203D08 Thorlab). The high stability of the confocal resonators makes this peculiar approach possible, without relevant

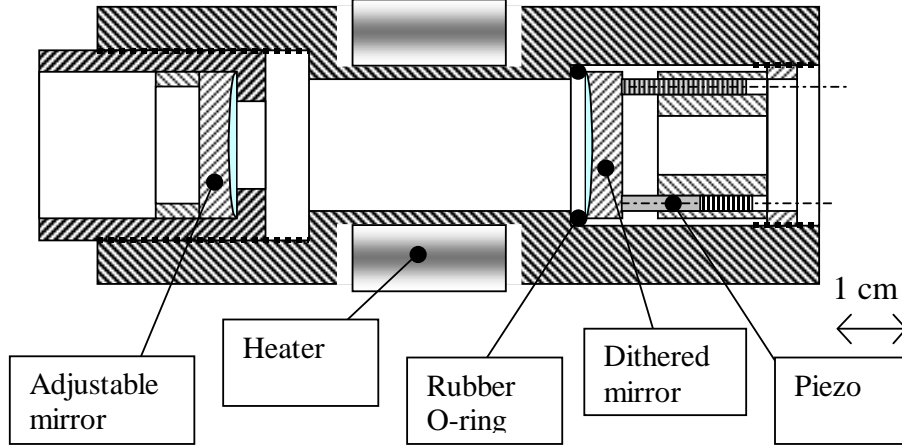


FIG. 2: Schematic of the mechanical mount of the Aluminium cavity.

detrimental effects on the quality of the observed spectra.

A part of the aluminium tube – where the heater is mounted – has a thinner wall. This reduced thickness (about 1mm) is essential to achieve a suitably fast response to the thermal control. The heater consists of eight 2 W, 100 Ω resistors, tightly fold onto the tube, powered with up to 10 W. The thermal contact between resistors and tube is improved by means of thermal silicon grease for electronic purposes.

B. Detection and acquisition

A photodiode detects the transmitted light from the FP interferometer and the photocurrent is converted into a voltage signal *via* an operational amplifier, whose output is directly acquired by computer.

In our present application, only one laser has to be stabilized and a scan over a FSR is sufficient for the application, so that a single photodiode is used and the peaks of both the master and the slave lasers are acquired in a single trace. If more slave lasers have to be stabilized, or if tunability on a wider range than a FSR is requested, the different lines can be sent on different filtered photodiodes, and the program can be modified in order to acquire more traces separately.

The signal from the photodiode is acquired as an array of 1000 values (this value can be adjusted), and a second ADC channel acquires the signal driving the piezo actuator in a similar array.

The signal of the waveform generator is a triangular wave at a frequency of about 10 Hz, (this is much lower than the measured mechanical resonance of the piezo-mirror system, which is around 800 Hz). The triangular wave amplitude is 24 V peak-to-peak, and it is enough to scan over more than a FSR.

No high-voltage signals are needed, and a commercial signal generator is used. It is worth stressing that possible small deviations in the signal slope or amplitude do not affect precision as the transmittance is detected together with the signal itself, so that the spectrum is plotted as a function of the actual voltage applied to the piezo. This choice makes the stability of the waveform generator not crucial, nevertheless in our case the generator is stable enough, and this detail turned out to be not essential for the final performance.

The stabilization system provides a current which – through the heater – keeps the cavity length constant, and a voltage which drives the slave laser frequency. These two signals are produced according to different philosophies. Namely, the cavity length is kept constant by keeping a transmission peak of the master laser *close* to the position selected by the operator, while the slave laser peak is *precisely* kept at a given distance from the master laser peak. In fact, the stabilization of the cavity length does not demand absolute precision, having only the aim of keeping the peaks within the scanned range, while the distance of the peaks gives an error signal which is neither affected by possible low-frequency noise in the triangular wave, nor by slight oscillations of the cavity temperature (and hence average cavity length).

As the cavity length is scanned over more than one master-laser half-wavelength, it is possible to monitor two master-laser peaks. The measured distance between two adjacent master-laser peaks (FSR) allows for a precise calibration of the frequency axis on the monitored spectra.

C. Computer program and analysis of the performances

The program was developed using LabView and runs on a Pentium III processor working at 1 GHz clock frequency. The computer works with a 16-bit ADC card, model NI 6052E; we also checked the program with a cheaper ADC card (namely the 12-bit NI LabPC+) obtaining comparable performances. The logic of the program is summarized in Fig. 3.

The program acquires both the slope of the waveform generator and the FP pattern, then calculates – in terms of the voltage on the slope – the absolute position of the He-Ne peak

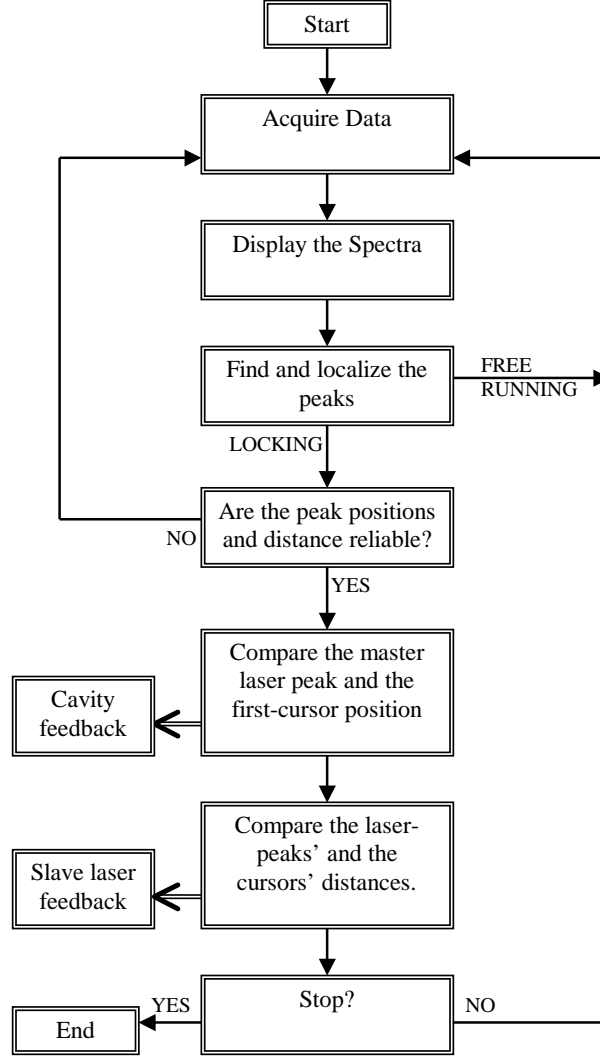


FIG. 3: The scheme summarizes the logic followed by the program in stabilizing the cavity length and the slave laser(s) frequency. For each scan of the piezo driving voltage, the spectra are displayed and analyzed. The peaks are detected and their position and relative distance is calculated. The feedback signal to the cavity thermal control is updated depending on the position of the master laser peak, while the feedback for the slave laser(s) is calculated using the distance of the master peak and slave peak(s). The cycle is directly restarted with no updating of the output when the detection of the peaks is not reliable, e.g. due to noise glitches, accidental shutting of a beam, etc.

and the distance between the He-Ne peak and the slave laser peak. By comparing these two data with the nominal values, the program calculates the two feedback signals for the FP thermal stabilization and the slave laser stabilization. The nominal values are set by means of two cursors. The position of the first cursor sets the position of the master laser peak,

and hence the cavity length, while the second cursor sets the position of the slave laser(s) peak, and hence the final frequency.

Each acquisition consists in n scans (we used $n = 1000$) and the program takes 10 acquisitions per second, while refreshing the feedback signals at the same rate. The sampling rate is 20000 samples per second. All the data and the corrections to the feedback signals are reported on the screen, which is also refreshed after each acquisition.

If the program finds problems in calculating the peaks' position (e.g. due to glitches originated by the laboratory electric noise affecting the photodiode signal), it leaves the feedback signals unchanged and goes to the next acquisition; if the problem persists for several cycles the program alerts the user, with a permanent alarm which is manually resettable, and a counter reports the number of cycles which gave problems.

The feedback signals consist of two voltages varying between -5 and 5 V. One of these signals is sent directly to the external control of the slave laser, the other is converted by a voltage-to-current amplifier to supply the cavity heater. The algorithms which calculate the correction of the two signals are different: the thermal stabilization needs only a correction proportional to the deviation of the He-Ne peak from the selected position, and the thermal capacitance of the FP cavity provides an integration of the discontinuities of the output voltage by itself. The stabilization signal sent to the slave laser needs a more advanced algorithm: the program must integrate the output signal to keep the laser frequency stable over the short-time range. This is achieved by limiting the maximum slope of the correction signal, which can be optimized by the user, according to the typical drift velocity encountered in the internal stabilization system of the laser.

When necessary, the program makes it possible to scan the laser voltage from -5 V to 5 V, searching for a reference signal (for example the fluorescence of the MOT) to set the unknown value of the right laser voltage automatically; obviously the user has to stop the laser stabilization before running the program with this aim.

The scan operation will have an important role in the application in the francium experiment. In fact, the locking procedure will start by using a wave-meter in order to set the laser frequency in resonance with an uncertainty of several hundred MHz. Then the control of the laser will be passed to the program, which will scan the frequency over a range just wider than the wave-meter uncertainty, looking for the exact resonance. During the scan, the frequency will be referenced with respect to the He-Ne peaks. Once a known resonance is

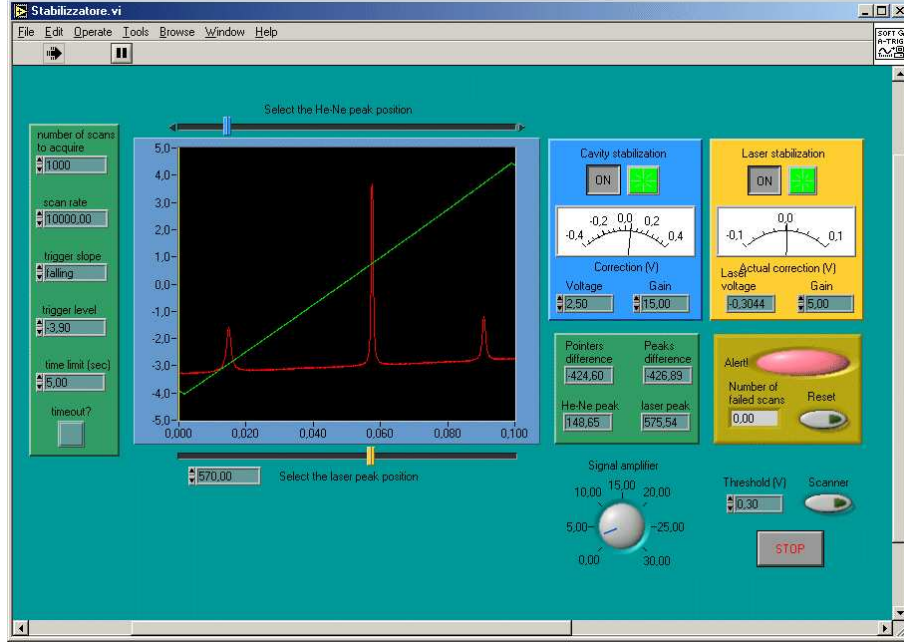


FIG. 4: This is the window shown to the user, which allows him to control the program. On the left side there are controls for the scan rate, the number of scans (abscissa points), the trigger, and trigger time-out. The spectra are shown in the central panel together with the piezo ramp. Two cursors above and below this central panel allow for placing and displacing of the peak positions. On the right side, on the upper part there are two panels with switches for starting the stabilization of the cavity and slave laser respectively, and two indicators showing the actual error signals. In the lower part the nominal and actual peak positions are reported in one panel, while on the other panel an alert goes on when locking fails, and a counter reports the number of failed scans. Finally a knob makes it possible to adjust the gain on the photodiode signal, and the trigger threshold can be set numerically from an input close to the "stop" button. Another button starts the scan operation.

found, the program will provide an absolute frequency scale, which will keep being available as long as the He-Ne laser stabilization system of the cavity is kept on. Finally the frequency will be locked to the exact value, and the program will provide the error signal necessary to maintain long-term stability. A user-friendly graphic interface (see Fig. 4) makes use of a few numerical controls and cursors, which allow for

- locking of the cavity with respect to the He-Ne FP peaks;
- scan of the slave frequency in a given interval;

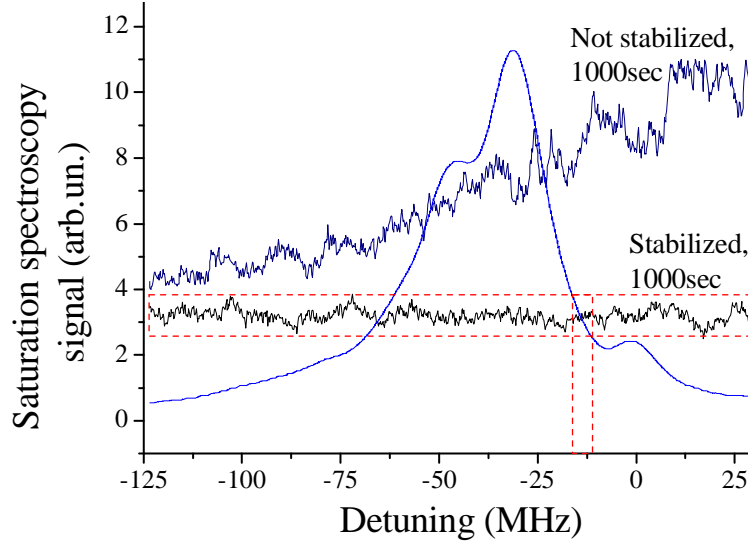


FIG. 5: The achieved frequency stability of the laser is estimated by measuring the fluctuation of the saturation spectroscopy signal on a Na cell. The figure shows a spectrum and the location at which the laser was stabilized (red wing of the D_2 , $F = 2 \rightarrow F' = 3$ transition). Also two traces are reported of 1000 s obtained in conditions of stabilized and not-stabilized operation respectively. The boxes show that the frequency varies within a range of 4 MHz when the stabilization system is on. This is probably an overestimation due to uncontrolled fluctuations in the reference cell, in fact the fluorescence of the MOT was extremely stable, even using detuning close to the edge of the trapping range.

- fast setting and precise adjustment of the stabilization point.

III. RESULTS

Fig. 5 reports the saturation spectroscopy signal obtained by scanning the laser frequency over the D_2 , $F_g = 2 \rightarrow F_e = 1, 2, 3$ lines of sodium [6]. Two traces of the same signal are also reported as obtained by keeping the frequency at a nominal fixed value, either with the stabilization system on or off. The recording time for these two traces is 1000 s.

Short term deviation of the laser frequency as deduced from these plots is definitely less than ± 2 MHz, as graphically shown by the dashed boxes. Statistical analysis on the trace recorded in stabilized conditions shows that the ratio between the standard deviation and the range of values is less than 0.15, corresponding to a standard deviation of 600 kHz in

the frequency scale.

These estimations of the frequency deviation may be larger than the actual values, because other effects produce some noise on the saturated spectroscopy signal. In fact, a relevant noise level is also visible on the wing of the saturation spectroscopy signal, which at detunings larger than 100 MHz, should be nominally zero.

The short term (few seconds) deviations of the frequency appear with similar features both in the stabilized and in the not-stabilized operation, so that they are probably intrinsic in the internal stabilization system of the laser; the comparison of the two curves in Fig. 5 show that they are only partially reduced by our external device, which on the contrary definitely fixes the long-term drift.

We performed a cross-check of stability using the fluorescence signal of the atoms trapped in a MOT using the $F_g = 2 \rightarrow F_e = 3$ transition of the D_2 line of the sodium. By displacing the slave laser frequency in steps of 2 MHz, it was possible to evaluate in 14 MHz the total spectral width of the trap.

As also reported in [6], at the high-frequency side the trap abruptly disappears. In our observation we were able to keep the trap unstable on that condition, with a fluorescence signal significantly lower than the maximum, and essentially stable in time.

IV. DISCUSSION AND CONCLUSION

A cheap and easy-to-use set-up was developed which, coupled with an efficient computer program, a commercial ADC-DAC card, and a standard confocal FP interferometer allows for active long term stabilization of one or more laser frequencies. A long term stability better than 4 MHz was demonstrated, and a FWHM of 1.2 MHz was achieved in the statistical distribution of the stabilized frequency. The short term stability keeps being given by the internal, fast stabilization system of the ring dye laser used as a slave.

The peculiar approach which stabilizes the relative peak position of the master and slave laser(s) reduces the effect of low frequency noise in the driving voltage applied to scan the piezo, and makes ultra high accuracy on the cavity length stabilization unnecessary, so that only a slow and not high precision thermal feedback must be used, in order to always keep given interference orders within the scanned range.

The final stability which is achieved with this technique is in excess with respect to the

demands of the experiment to which this technique was applied. Further improvements could be made by using a longer cavity and separate photodiodes for the acquisition of the peaks corresponding to different lasers, and setting up FP with a smaller FSR. In fact with the single photodiode operation the adjustable range is limited by one FSR, as no superposition of peaks is allowed.

We address to [3] for a detailed analysis of the limitations on long term stability which are set by the effects of atmospheric pressure and humidity, whose variation may introduce errors due to different changes of air refraction index for the different wavelength of the laser used. Variations in atmospheric temperature are also potentially critical, but this problem is definitely overcome in setups where a close cavity is thermally stabilized. In our case the difference in the two wavelengths is smaller than the one reported in [3], thus reducing the effect due to dispersive refraction index of humidity.

Acknowledgments

The authors thank all the colleagues of the Siena, Ferrara and Legnaro laboratories for the encouragements and the useful discussions. Evro Corsi and Alessandro Pifferi are thanked as well, for their effective technical support.

-
- [1] W. Demtroeder; *Laser Spectroscopy*; Springer-Verlag Ed. (1982).
 - [2] W. Zhao, J. E. Simsarian, L. A. Orozco, and G. D. Sprouse; A computer based digital feedback control of frequency drift of multiple lasers; *Rev. of Scient. Instr.*, **69**, 3737, (1998).
 - [3] E. Riedle, S. H. Ashworth, J. T. Farrel Jr., and D. J. Nesbitt; *Rev. of Scient. Instr.*, **65**, 42, (1994).
 - [4] S. N. Atutov, V. Biancalana, A. Burchianti, R. Calabrese, L. Corradi, A. Dainelli, V. Guidi, B. Mai, C. Marinelli, E. Mariotti, L. Moi, A. Rossi, E. Scansani, G. Stancari, L. Tomassetti, S. Veronesi; Production of Francium ions for TrapRad; Annual Report INFN-LNL 2001, in press; L. Moi, S. N. Atutov, V. Biancalana, A. Burchianti, R. Calabrese, L. Corradi, A. Dainelli, V. Guidi, B. Mai, C. Marinelli, E. Mariotti, A. Rossi, E. Scansani, G. Stancari, L. Tomassetti, S. Veronesi; *Laser Cooling and Trapping of Radioactive Atoms*; SPIE, *Proceed. of XVII int. Conf. on Coherent and Nonlinear Optics* (Minsk 26/06-01/07 2001).

- [5] M. Born and E. Wolf, Principles of Optics, 6th. ed. (Pergamon Press, Oxford, 1987).
- [6] S. N. Atutov, V. Biancalana, A. Burchianti, R. Calabrese, S. Gozzini, V. Guidi, P. Lenisa, C. Marinelli, E. Mariotti, L. Moi, K. A. Nasyrov, S. Pod'yachev; Eur.Phys.J. **D 13**, 71,(2001).